Displaced-Phase-Center Antenna Technique

Charles Edward Muehe and Melvin Labitt

This article describes Lincoln Laboratory contributions to the development of the displaced-phase-center antenna (DPCA) technique, which was used to improve the detection performance of airborne or space-borne MTI radars that are subject to clutter. In the 1950s the DPCA technique was applied to airborne early warning (AEW) radars for defense of North America against long-range bombers carrying nuclear weapons. Lincoln Laboratory built the first UHF AEW radar, which became the prototype for both Air Force and Navy operational radars. In the 1970s, experience during the Vietnam war showed the possible usefulness of a wide-area surveillance radar to monitor moving ground vehicles. DPCA radar theory and the emergence of medium-scale digital signal processing showed the feasibility of such an airborne radar. Lincoln Laboratory proceeded to design and test a Multiple-Antenna Surveillance Radar (MASR). The Air Force then built a developmental DPCA radar called Pave Mover, which was followed by the currently operational Joint Surveillance and Target Attack Radar System (Joint STARS). In the 1980s, space-based radar showed potential for a variety of applications, including early detection of aircraft raids against Navy battle groups and the detection of moving ground targets such as mobile missile launchers. The DPCA technique allowed the use of smaller, cheaper satellites at lower altitudes than the conventional high-altitude, pulse-Doppler radar. Antennas were designed and their clutter-cancellation capabilities measured and compared with theory. A new technique for calibrating remote phased-array antennas, called the mutual-coupling technique, was discovered.

The displaced-phase-center antenna technique, or DPCA, improves the performance of moving-target-indicator (MTI) radars mounted on moving platforms. By shifting the effective radiation center of the antenna backward, the DPCA technique compensates for the forward motion of the moving platform so that, over a few pulse-repetition intervals, the antenna is effectively stationary in space. The lack of motion of the radiating antenna causes a great narrowing of the spread of the main-beam ground-clutter Doppler spectrum, allowing detection of low-velocity targets that would otherwise be hidden within the spectrum.

In this article we are using the acronym MTI in a generic sense, in reference to any technique that would indicate (show or make known) moving targets that might otherwise not be observed because of clutter. Before the invention of MTI, the radar operator utilized another indicator, the plan position indicator (PPI), which displays the radar output in range-azimuth coordinates on a cathode-ray tube with a long-persistence phosphor. The operator recognized a moving target by a series of bright spots, caused by individual pulses, arranged in an arc spanning the antenna's beamwidth. The long-persistence phosphor trace shows the target's position on succeeding scans, indicating the speed and direction of the moving target. Much of the activity observed on the PPI represents reflections from the ground, rain, and birds, which the operator learns to ignore.

Historically, two types of MTI were invented and used with stationary radars: delay-line MTI and filter-bank MTI. The first type, invented near the end of World War II, utilizes an acoustic delay line with a delay equal to the interpulse period. In receive mode the reflected signals are stored in the delay line and subtracted from the returns of the next transmitted pulse with the result displayed on the PPI. All airborne MTI systems at that time were noncoherent clutter-referenced, responding only to the amplitude changes that typically resulted from interactions between the moving target and any nonmoving clutter in the same range gate. With clutter that was roughly the same size as the target, the changing relative phase between the target and the clutter returns would cause an amplitude fluctuation that could be detected by the noncoherent delay-line canceler. In the absence of clutter, MTI sensitivity was substantially reduced, particularly for targets flying tangentially with respect to the radar. However, the returns from moving clutter such as rain and birds often appeared on the PPI. Delay-line MTI was used principally on low pulse-repetition-frequency (PRF) radars and provided unambiguous target range.

The second type of MTI radar utilizes a medium or high PRF in which the true target range may lie in any one of several successive range intervals determined by the interpulse delay time. In receive mode, pulse-to-pulse sampling of each range-resolution cell provides signals to a bank of Doppler filters. In high-PRF radars, target signals from the same Doppler filter on two or more different PRFs but from different range cells are used to remove the range ambiguity. In medium-PRF radars, target range and velocity are both ambiguous and returns on several PRFs are typically used to estimate their true values. This type of MTI radar is frequently called a pulse-Doppler radar.

Before about 1970, when medium-scale digital integrated circuits became available, both of these MTI techniques were implemented by using analog circuits. By this time the beacon-reply function on the Federal Aviation Administration (FAA) Airport Surveillance Radars, operating at a low PRF, had been modernized with digital circuitry and provided output for automatic target-track initiation and update. However, the digital delay-line MTI, although more stable than the analog version, produced too many missed detections and false alarms from moving clutter to allow automatic tracking. For the FAA, Lincoln Laboratory designed a new class of low-PRF radars named the moving-target detector (MTD) by using the digital-filter-bank approach and novel constant-false-alarm-rate (CFAR) techniques that fully supported automatic target tracking. Since then most new surveillance radars, at all PRFs, utilize the filter-bank MTI.

Airborne-Early-Warning Radar (1952–1959)

Beginning in the 1950s a major concern for the United States was the defense of North America against long-range bombers carrying nuclear weapons. In 1952 a Summer Study Group [1] identified two problems with existing airborne surveillance radars: (1) the radars were unable to detect targets in clutter, and (2) the manpower-intensive systems used for detection, tracking, reporting, and intercept control could handle only a small number of targets. Lincoln Laboratory then became involved in research in airborne early warning (AEW) techniques.

UHF versus S-Band

When Lincoln Laboratory became involved in the AEW program in 1952, it was apparent that existing S-band AN/APS-20 airborne radars installed in the Navy WV-2 Super Constellation aircraft received massive amounts of sea clutter. It was known that if the radar operated at a lower frequency the clutter intensity could be reduced along with the width of the clutter spectrum. Consequently, a program headed by Jerome Freedman was started at Lincoln Laboratory to implement and compare the performance of airborne radars at both UHF- and S-bands, and to solve the clutter problem. An initial frequency of 425 MHz was chosen because of the availability of the Western Electric 7C22 triode oscillator. Later the QK-508 UHF magnetron specially built by Raytheon for Lincoln Laboratory was used. Tests soon showed a marked reduction in clutter at UHF [2].

Invention of TACCAR

The GE experiments described in the sidebar entitled "Invention of the DPCA Technique" showed that

INVENTION OF THE DPCA TECHNIQUE

PRIOR TO THE INVENTION of the displaced-phase-center antenna technique, or DPCA, airborne radars that utilized moving-target indicator (MTI) suffered from the butterfly effect, a phenomenon associated with clutter leakage that causes wing-shaped patterns to appear on a plan position indicator (PPI) display. The Doppler frequency of a reflected clutter return varies as the cosine of the angle between the direction of the clutter return and the aircraft's velocity vector. Pointing forward, the main-beam clutter spectral spread is quite narrow; pointing abeam it is quite wide. The broader clutter spectrum abeam causes more clutter leakage through the delay-line MTI filter, which results in the wing-shaped pattern.

General Electric (GE) is generally credited with inventing the DPCA technique to largely eliminate the butterfly effect [1]. In 1952 GE Electronics Laboratory in Syracuse, New York, was working to improve MTI on a ground-based mortar-locating radar through a study for the Army Signal Corps called "Anti-Clutter Techniques." The study noted that by adding and subtracting the output of the azimuth difference port to the output of the azimuth sum port of a monopulse antenna, two beams—a leading beam and a trailing beam—could be formed. At the proper separation angle and with the antenna rotating, signals from the trailing beam could be received at exactly the same pointing angle as the previously received signals from the leading beam. Subtracting the two signals should largely cancel the clutter. GE engineer F.R. Dickey [2] noted the similarity of this problem caused by rotation to the butterfly effect caused by translation in airborne MTI. This observation led him to propose using a monopulse antenna for motion compensation of the airborne MTI radar platform, a technique later named DPCA.

In 1954 the Air Force authorized GE to modify an AN/APS-27 X-band, monopulse airborne radar to include the DPCA technique. This radar used noncoherent MTI that subtracted the normal video signal from pulse to pulse to form the MTI output. Test flights that took place in 1956 successfully showed the reduction of clutter expected from the use of the DPCA technique.

References
1. F.R. Dickey, Jr., M. Labitt, and F.M. Staudaher, "Development of Airborne Moving Target Radar for Long Range Surveillance," *IEEE Trans. Aerosp. Electron. Syst.* **27** (6), 1991, pp. 959–972.
2. F.R. Dickey, Jr., and M.M. Santa, "Final Report on Anti-Clutter Techniques," General Electric Co. Report R65EMH37, 1 Mar. 1953. (The number refers to a 1965 reprint.)

noncoherent MTI works moderately well in the presence of strong fixed clutter, but only sporadically in the presence of weak clutter. Thus Lincoln Laboratory researchers attempted to make signals passing through the MTI canceler coherent by locking a coherent local oscillator (or COHO) to the phase of the return from a single range-gate sample of clutter. The COHO then ran at its own frequency until reset in phase by the clutter sample following the next transmission. This technique did not work well because of the finite width of the main-beam clutter spectrum. The COHO locked onto a spread of Doppler frequencies and produced ugly radial streaks on the PPI.

A solution for the streaking problem was found by deriving the COHO phase from the average phase of a large number of clutter range elements. This technique, which became known as Time-Averaged Clutter-Coherent Airborne Radar (TACCAR), was conceived by one of the authors, Melvin Labitt [3].

Two kinds of TACCAR evolved: first the video version, then the intermediate-frequency (IF) version. In both versions the COHO was phase-locked to the magnetron output pulse as in a standard coherent-on-receive ground-based radar. A voltage-controlled crystal oscillator was mixed with the COHO signal to provide the proper Doppler offset to correct for the aircraft motion. The difference between the two versions of TACCAR lay in how the error signal, needed to control the oscillator, was produced. In the video version of TACCAR the error signal was generated by using the video outputs of two identical phase detectors, the first fed by the COHO and the second by the COHO shifted by 90°. After passing through the single-delay-line MTI, the output of the first detector was multiplied by the output of the second. The multiplier output, after passing through a gate that selected the desired range of video signals and a 0.1-Hz low-pass filter, became the error signal used to control the crystal oscillator. In the IF TACCAR, a concept initiated by Melvin Herlin of Lincoln Laboratory, the IF passed directly through the delay-line MTI and was then compared with the undelayed IF in a phase detector. The phase-detector output passed through the range gate and low-pass filter to provide the error signal. The IF TACCAR performed better than the video TACCAR because it eliminated a blind-phase target-detection problem associated with the use of a delay-line canceler on one of the two possible phases of the video target signal.

The accuracy of TACCAR depends on the number of range gates sampled. The Doppler error or spectral spread increases inversely with the square root of the number of gates. Using sets of gates, each in a contiguous area having similar depression angles, allows depression-angle Doppler correction. However, depression-angle correction was not implemented in the original system because the system worked well enough without it.

Addition of the DPCA Technique

With the addition of TACCAR to the UHF airborne radar the subclutter-visibility measurements showed values of 18 to 20 dB when the antenna was pointing in the direction of the aircraft's motion but only 12 dB normal to the aircraft's motion, and the PPI displayed a significant butterfly effect. For these measurements, an antenna supplied by the Naval Research Laboratory consisted of fourteen dipoles along the focus of a parabolic cylinder. Feeds for each half of the dipoles (seven) were connected to a hybrid junction to provide sum and difference received signals. To effectively displace the phase center of the antenna for best DPCA performance, a special RF modulator was built to add the correct value of the difference signal to the sum signal as the antenna rotated. Since the antenna was not designed for the DPCA technique, it was clear that this arrangement was an approximate solution. Nevertheless, with the DPCA technique the subclutter visibility normal to the ground track was increased dramatically to within a few dB of the ground-track value.

Operational Results

In mid-1959 Lincoln Laboratory ended its AEW program because feasibility had been demonstrated and the technology was ready for production by industry. At this point, Lincoln Laboratory had operated UHF TACCAR AN/APS-70 systems in planes, blimps, and ships at sea. Figures 1, 2, and 3 show installations in a Navy WV-2 aircraft, in a Navy blimp, and with a 30-ft antenna in a WV-2E aircraft.

Both the Air Force and Navy utilized the UHF

FIGURE 1. The WV-2 aircraft, an original carrier of the UHF AN/APS-70. A 17 × 4-ft antenna is mounted below the aircraft inside the black radome.

FIGURE 2. Navy blimp installation of the AN/APS-70 radar. The radome appears at the bottom of the blimp.

FIGURE 3. The AN/APS-70 radar mounted aboard the WV-2E aircraft. The antenna, measuring 30 feet in diameter, was the biggest airborne antenna of its day. From left to right are Henry Rempt of Lockheed, Jerome Freedman of Lincoln Laboratory, and Lt. Cmdr. R.L. Warner, U.S. Navy.

Lincoln Laboratory radar as an AEW prototype. The Air Force AN/APS-95 was mounted in Lockheed's RC-121D Super Constellation aircraft, shown in Figure 4. These aircraft flew for many years along the east and west coasts of the United States.

In 1957, the Navy awarded a contract to Grumman Aircraft Engineering Corporation to develop what became the E-2A carrier-based AEW aircraft [1]. The Light Military Electronics Department of GE received a subcontract to develop the detection system and integrate the total electronic payload of the aircraft. That payload also included a limited capability to control an air battle from within the AEW aircraft, which merited the addition of the letter C to become AEW&C. Litton received a contract to develop the required computers, software, and consoles, all to be shoehorned into the fairly small fuselage of the carrier-based aircraft.

The first version was the UHF AN/APS-96 radar, which used a stable coherent master-oscillator/power-amplifier system and had IF TACCAR. The DPCA technique was not initially considered necessary for over-the-sea operation. The radar's amplifier transmitter (based on an RCA tetrode) allowed use of linear-FM pulse compression, yielding short compressed received pulses. The corresponding sharper range resolution reduced the amount of sea clutter in which target echoes were imbedded. Furthermore, an estimate of a target's height (essential for the AEW&C function) could be made by using an algorithm based on the time difference between receipt of two or three separate echoes caused by multipath propagation over the reflecting sea surface. A subsequent version of this radar utilized a double-delay-line MTI canceler with the DPCA technique and other improvements to greatly improve subclutter visibility and allow overland operation. The production version was dubbed the AN/APS-120. Over the years this radar has been upgraded to include a digital fast-Fourier-transform (FFT) coherent integration, electronic counter-countermeasures (ECCM), and improved post-detection processing. Figure 5 shows the current version of the AN/APS-145 aboard the E-2C Hawkeye aircraft.

FIGURE 4. AN/APS-95 radar installed in a modified Lockheed Super Constellation aircraft.

FIGURE 5. The E-2C Hawkeye aircraft shown returning to its carrier from a mission. With its displaced-phase-center antenna (DPCA) overland radar, the aircraft can track more than 2000 targets at once and monitor three million cubic miles of airspace.

An interesting comparison can be made between the Navy AN/APS-145 surveillance radar and the Air Force AN/APY-2 radar, part of the AWACS (Airborne Warning and Control System). The Navy radar is a low-PRF UHF (0.7-m wavelength) radar, while the Air Force radar uses a high-PRF S-band (0.1-m wavelength) radar with an elevation-angle scanning antenna. The high-PRF Air Force radar produces no Doppler or target-velocity ambiguities but has range ambiguities at intervals of about 6 km so that multiple PRFs must be used to find the true target range. The Navy radar using low PRF has no range ambiguities out to its maximum search range; its longer wavelength results in target velocity ambiguities only about every 140 m/sec (280 knots), which are easily resolved by putting the detected targets in track. Because of the vertical scanning and the multiple PRFs, the Air Force radar requires much more radar power than the Navy radar. The AWACS aircraft carries the complete command-and-control center aboard. The Navy Hawkeye aircraft carries a crew of five and can perform limited command-and-control functions. The aircraft generally works in proximity to an aircraft carrier that performs most command-and-control functions. The much smaller Navy aircraft can land on a carrier deck and be stowed below deck. The Air Force radar does not employ the DPCA technique but relies on extremely low antenna sidelobes to eliminate clutter reflections that produce Doppler frequencies outside the main-beam clutter Doppler spectrum. The main beam is very narrow so that the main-beam ground-clutter spectrum represents a velocity spread only about 20 m/sec (40 knots) wide.

Airborne Ground-Surveillance Radar (1970–1979)

Tactical reaction to battlefield situations requires continuous surveillance of the area of interest over an extended period with data on individual moving ground vehicles that are rapid and accurate enough to establish tracks. In 1970 no branch of the military possessed an airborne ground-surveillance radar that provided continuous coverage of moving ground vehicles.

Synthetic-aperture radar was available only for fixed-target detection. Detection of moving vehicles required the comparison of two synthetic-aperture maps of the same area, a process called change detection. This process provided only intermittent looks at an area, and too much time passed between looks to permit immediate tactical reaction against the moving targets. The Army had an airborne-MTI side-looking radar with a very narrow beamwidth, but fixed antenna, that produced a strip map of moving targets. Again, this radar did not provide enough timely information for tactical reaction against the moving targets.

The genesis of the Multiple-Antenna Surveillance Radar (MASR) program was a memo written by Walter E. Morrow, Jr., dated 8 May 1970. The memo recalled a recent series of interesting lunar and planetary radar measurements made at the Haystack radar facility in which interferometric techniques were used to remove ambiguities in range-Doppler maps of the planet Venus and were also used to permit height or topographic measurements of the lunar surface. The interferometer utilized a large auxiliary antenna some distance from the main Haystack antenna. Interference fringes were formed across the surface of Venus so that a null occurred at the source point for ambiguous reflections that cause errors in the range-Doppler map. Morrow proposed that interferometric techniques could permit the detection of slowly moving ground vehicles by airborne MTI radars without the use of very large airborne antennas.

Charles Edward Muehe replied with a memo dated 14 May 1970 that includes an analysis of the performance of an interferometer comprising two small side-looking antennas mounted on the side of an aircraft. For a moving target approaching the aircraft, competing ground clutter arrives from an azimuth forward of the target angle. Maintaining a null that occurs at the angle of the competing clutter requires the proper phase adjustment between the two side-looking antennas. It was shown that this phase adjustment could be accomplished by putting a time delay in the forward-antenna line equal to the time it takes for the aircraft to traverse the distance equal to the spacing of the two antennas. This time delay is precisely the one used in the DPCA technique.

A small study group researched previous developments to design such a radar and predict its perfor-

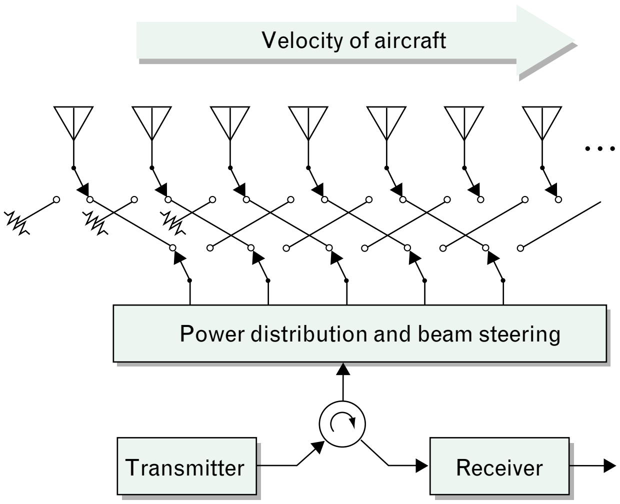

FIGURE 6. Configuration of the Multiple-Antenna Surveillance Radar (MASR). This design produce nearly identical antenna patterns when transmitting and receiving alternately from two phase centers.

mance. The group developed a detailed mathematical analysis of multiple-antenna airborne radar systems [4]. The clutter-covariance matrix was used to represent the clutter-cancellation degradation caused by a variety of radar imperfections. The most difficult design task was providing an antenna system with nearly identical antenna patterns when transmitting and receiving alternately from two phase centers.

The resulting design configuration is depicted in Figure 6. An array-type antenna electronically scanning in azimuth is mounted along the side of an aircraft. First a length of the forward portion of the array is utilized to transmit a pulse and to receive the signals reflected from the clutter and any targets. After the aircraft has moved forward a distance equal to an integral multiple of the element spacings (three in Figure 6) the set of switches is thrown so as to utilize an equal-length rearward portion of the array. The next pulse is transmitted and the signals received. With this arrangement the two pulses are transmitted from the same point in space so that there is no relative motion of the antenna between pulses. Theory shows that using the aircraft's inertial-navigation system allows the proper timing between pulses to be determined accurately even when the aircraft is in yaw due to cross winds. For accurate target location in azimuth the power-distribution and phase-steering network in Figure 6 includes independent sum and difference channels on receive.

With the encouragement and counsel of Herbert G. Weiss of Lincoln Laboratory and John Entzminger of Rome Air Development Center, the MASR concept was presented to the Air Force and hardware development was funded in 1973. Melvin L. Stone managed the project. Gerasimos N. Tsandoulas designed and tested the most critical element, the MASR antenna.

System Description

A clutter cancellation in excess of 40 dB was required for successful detection of targets moving on the surface of the Earth. To achieve this objective [5, 6], tolerances on the MASR L-band antenna components were set at 0.7° root mean squared (rms) in phase, 0.11 dB rms in amplitude, and 0.02 rms in magnitude of the reflection coefficients. The achieved tolerances and their reliable measurement were unprecedented in phased-array work and as such represented state of the art. Confirmation of antenna-beam identity between the two phase centers was obtained through actual detailed pattern (amplitude and phase) measurements in an antenna range.

Figure 7 shows the antenna in its operational environment. It is mounted on the side of a DeHavilland Twin Otter aircraft, which has a high wing structure that permits unimpeded scanning of the beam (±45°) in the horizontal plane and minimizes interaction effects that could compromise main-beam-pattern similarity between phase centers.

FIGURE 7. MASR antenna mounted on the side of a DeHavilland Twin Otter aircraft. The antenna measures 15 ft × 2.5 ft × 5 in and weighs 370 lb.

The antenna consists of 252 rectangular-waveguide radiating elements arranged in 42 vertical columns. Six radiating elements fit in one vertical column. Only about 76% of the total antenna aperture is excited by the transmitter at any one time. The remainder either participates in the phase-center-switching operation (two columns) or consists of terminated columns (four on either side) that stabilize the mutual-coupling environment at the array edges. Phase-center selection takes place in a high-isolation (>60 dB) two-pole diode-switch matrix and occurs ahead of the phase shifter, which is thus forced to contribute its errors identically to each radiated beam. A system of adjustable-only-once phase trimmers removed most of the residual antenna phase error after assembly.

The transmitted waveform is linear FM [7]. A surface-acoustic-wave (SAW) reflective-array compressor is used to affect the pulse expansion and compression. The combination of a large time-bandwidth product of 1500 and long 150-μsec pulses rendered the use of lithium niobate (conventionally used in SAW applications) inappropriate because of the extreme length of crystal required. An alternative technology was developed by using bismuth germanium oxide as a substrate material [8]. Two waveforms were provided, a narrow-bandwidth waveform for wide-area surveillance with 60-m range resolution and a wide-bandwidth waveform for accurate monopulse tracking over a smaller area with 15-m range resolution.

After analog pulse compression the received signals are digitized and processed in a parallel microprogrammed processor (PMP) [9]. The received signals from the leading and trailing antenna phase centers are grouped in pulse pairs. The differences from 32 pulse-pair subtractions are first weighted and then operated upon by an FFT algorithm to yield 32 Doppler channels, with a velocity resolution of about 0.4 m/sec. The result from each range gate is then thresholded and for each detection a report is generated and transmitted to the data processor on the ground. The version of the PMP employed had two processing elements, each capable of 25 million instructions per second with an instruction cycle of 75 nsec and of executing a 32-point FFT in 130 μsec. It could keep up in real time with the processing of 512 range gates, covering about 30 km in the wide-area surveillance mode.

The airborne portion of the MASR was accompanied by a ground-processing center that provided a wide variety of data-processing and radar-control functions. Control of aircraft orbit, radar mode, and antenna-scan pattern were exercised by using automatic algorithms or operator intervention. Among the operator specified tasks were (1) recording data received over the down link; (2) display of target reports on a map derived from a digital data base showing the major highways, aircraft position, and radar beam footprint; (3) shading of areas of the map that are invisible to the radar because of terrain masking; (4) monopulse azimuth estimation; (5) display of the output of real-time multiple-target tracking; (6) detection and display of a convoy of vehicles; (7) inertial-navigation system position updating; and (8) radar diagnostics and calibration.

Performance Evaluation

The MASR was subjected to extensive airborne testing. The radar was evaluated for its clutter cancellation, its detection of targets in clutter, its ability to

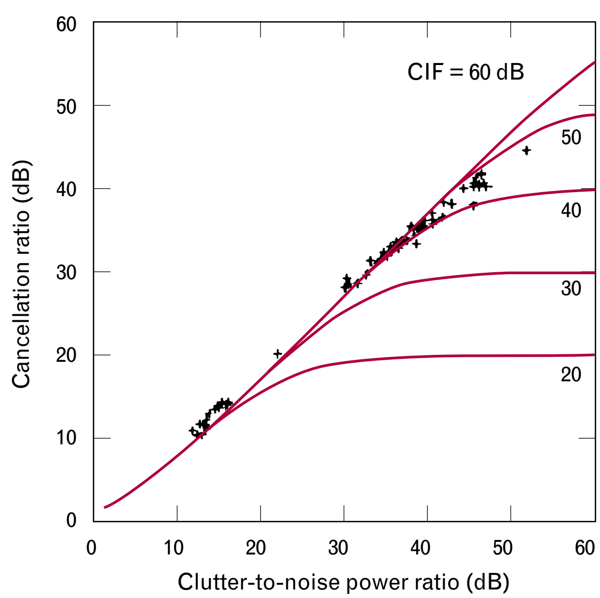

FIGURE 8. DPCA cancellation ratios. The crosses are measured ratios of input-to-output interference (clutter plus noise) as a function of input clutter-to-noise power ratio. The measured interference ratios indicate a clutter-improvement factor (CIF) of about 46 dB.

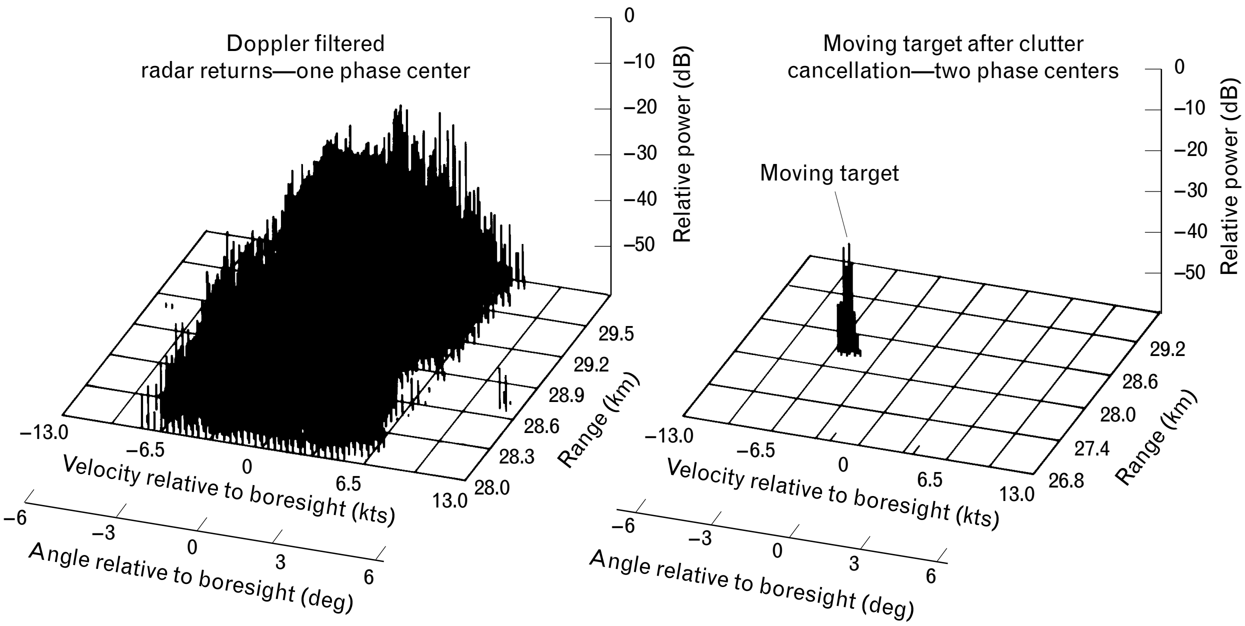

FIGURE 9. Range/Doppler display demonstrating clutter-cancellation property of the MASR DPCA system. Shown on the left is actual output of the signal processor using data from one phase center only; large ground-clutter returns are all that is detected. On the right is the result obtained by subtracting the processed outputs of two phase centers; clutter returns are canceled and the moving-target return, formerly embedded in clutter, is clearly visible.

track moving targets and report them in an earth-referenced coordinate system, and its ability to detect convoys of moving vehicles.

The cancellation ratio is defined as the ratio of clutter to noise at the canceler input to that at the canceler output. Figure 8 shows the measured cancellation ratio plotted as crosses. Experimental values of the cancellation ratio in each of 80 range cells were computed by averaging the input and residue output interference powers over 64 pulse pairs. The separate curves in Figure 8 indicate the expected results for various clutter-to-noise power ratios. From the figure the clutter-improvement factor (CIF) is approximately 46 dB. The experimenters complained that they couldn't find strong enough clutter to extend beyond the experimental points shown.

Figure 9 depicts the detection of an isolated moving target by means of clutter cancellation obtained by using the DPCA technique with the MASR. The Doppler-filtered returns from a single phase center are compared with the Doppler-filtered returns after clutter cancellation of the signals from two phase centers. Figure 9 has been used by many authors to illustrate DPCA clutter cancellation.

Target tracking offers a number of significant advantages in the processing of MTI radar data. It yields target position and velocity estimates that can be used to predict target position during intervals of missing detections. Improved knowledge of target dynamics is also obtainable, and velocity sorting and convoy detection can be performed. Convoy-detection experiments were staged on local highways by commingling test vehicles traveling at prescribed speeds and separations with the normal traffic flow. When the ranges and velocities of all of the vehicle tracks in a small area were plotted as functions of time, a seven-vehicle convoy could clearly be discerned by the grouping of the curves of the convoy vehicles. A convoy-detection algorithm using vehicle number, separation, and ground speed as selection parameters was quite successful in discriminating between the convoy and the normal highway traffic.

The Adaptive DPCA Technique

During the MASR development J. Russell Johnson, in an internal memo of 5 March 1976, suggested a change in the order of processing signals, performing the FFT prior to subtraction of the signals from the two phase centers. A synthetic-aperture antenna is mounted on the side of a moving platform and receives data from a single phase center. Performing an FFT on the data sampled from a single range gate divides the real antenna's beam into as many synthetic beams as the order of the FFT. By using adaptively chosen weights, the stationary ground-clutter signals from each range gate may be minimized by coherently subtracting the output of the synthetic beams received on two phase centers. A postscript to Johnson's memo states that this combination of synthetic-aperture radar (SAR) and DPCA technique was apparently first suggested for use on VHF foliage penetration radars by Carlyle J. Sletten of Air Force Cambridge Research Laboratory in a June 1969 memo. This combination was named arrested synthetic-aperture radar (ASAR).

The ASAR approach provides as many parameters to adaptively adjust the effective real antenna beam shape as the order of the FFT and would significantly reduce the required construction accuracy of the MASR antenna. ASAR requires considerably more digital processing than used in the MASR but would be feasible with present-day digital processing. This technique was not implemented in MASR, although it was exercised off-line with data collected from MASR and found to operate as predicted by theory.

We next discuss solutions suitable to overcome both types of ambiguous clutter returns—Doppler and range. Doppler-ambiguous clutter returns occur if the PRF is lower than the Doppler width of the main beam's clutter spectrum. The Doppler spread of a beam is given by $\Delta f_d = (2V \sin\theta \, \Delta\theta)/\lambda$, where V is the platform velocity, θ is the beam pointing angle with respect to the platform velocity vector, $\Delta\theta$ is the azimuth beamwidth, and λ is the radar wavelength. As the real antenna of active length a is steered away from direct broadside, its beamwidth is given by $\theta_b = K\lambda/(a \sin \theta)$, where K (typically about 3) is the ratio of the transmit/receive beamwidth between the antenna's first nulls to its nominal beamwidth at broadside, λ/a. For any beam position not too far from broadside, θ_b can be equated with $\Delta\theta$ to approximate the Doppler spread as $(2KV)/a$. Note that the main-beam Doppler spread is independent of both the wavelength λ and the pointing angle θ of the real antenna beam. The ratio $(2KV)/a$ is the lowest PRF that can be employed while avoiding mainlobe Doppler foldover into the set of clutter filters. These sidelobes of the product of the transmit and receive antenna patterns must be designed low enough to avoid deterioration of the DPCA performance by ambiguous sidelobe clutter.

Range-ambiguous clutter is from multiple-time-around clutter returns from the second-to-last and earlier transmitted pulses. MASR was not subject to either Doppler- or range-ambiguous clutter because of the relatively low altitude and speed of its airborne platform. The MASR's PRF could be chosen higher than that required to eliminate Doppler-ambiguous clutter but low enough so that second-time-around clutter returns were negligible. The MASR employed a switched-beam DPCA technique in which both transmit and received beams alternated between two antennas. Thus while the rear antenna was operative (i.e., it transmitted pulses and received the short-range clutter returns) the second-time-around clutter return from the previous pulse had been produced by transmission from the forward antenna but was received on the rear antenna. This cross-product return would cause significant adaptive-DPCA error for higher-flying and faster-moving platforms. A solution was found wherein the transmit beam always uses the whole array, and simultaneous received beams are employed with phase centers equally spaced on either side of the antenna's center. This is called simultaneous-beam DPCA.

FIGURE 10. Air Force Joint Surveillance and Target Attack Radar System (Joint STARS) aircraft. Note the DPCA antenna mounted forward under the fuselage. Image courtesy of Northrop Grumman Corporation.

William J. Ince and J.R. Johnson compared the performance of a long-range airborne surveillance radar utilizing switched-beam DPCA, simultaneous-beam DPCA, and single-beam (monostatic) antennas. With the DPCA technique it was found that the minimum-detectable-velocity (MDV) target has one-tenth to one-fifth of the MDV of the radar using a monostatic antenna. The study also showed that the angular error caused by using the DPCA technique and Doppler measurements to estimate a target's angle is about two-thirds the error of a monostatic monopulse antenna of the same size.

Operational Results

As a result of the successful development and testing of the MASR, the Air Force commenced the development of an operational prototype under contracts to Grumman Aircraft and Norden Systems (currently Northrop Grumman). First an advanced development model called Pave Mover was built and tested. This model was followed by the development of the Joint Surveillance and Target Attack Radar System (Joint STARS) [11].

Joint STARS features a 24-ft long, 2-ft high DPCA mounted on the forward under-fuselage of an Air Force E-8A (a modified Boeing 707-320), as shown in Figure 10. Initially two E-8As were built as development Joint STARS; the first successful flight took place in December 1988. Joint STARS utilizes the higher X-band frequencies rather than the MASR L-band. This higher frequency band allows imaging of stationary targets by using conventional SAR. It also results in detection of lower-velocity targets and better target location for a given size array, at the expense of some degradation in the detection of moving targets in heavy rain.

On 17 December 1990 General Norman Schwarzkopf requested Joint STARS support for the Persian Gulf Operations. On 12 January 1991 the two developmental test aircraft arrived in theater and flew their first sortie on 14 January 1991. They continued operations under combat conditions as the U.S. forces and their allies drove Iraqi forces out of Kuwait. Figure 11 shows the retreating forces in what then Secretary of Defense Richard Cheney called the "mother of all retreats." The two Joint STARS test aircraft flew 49 sorties, logging 535 flight hours before returning to their operational testing in Europe.

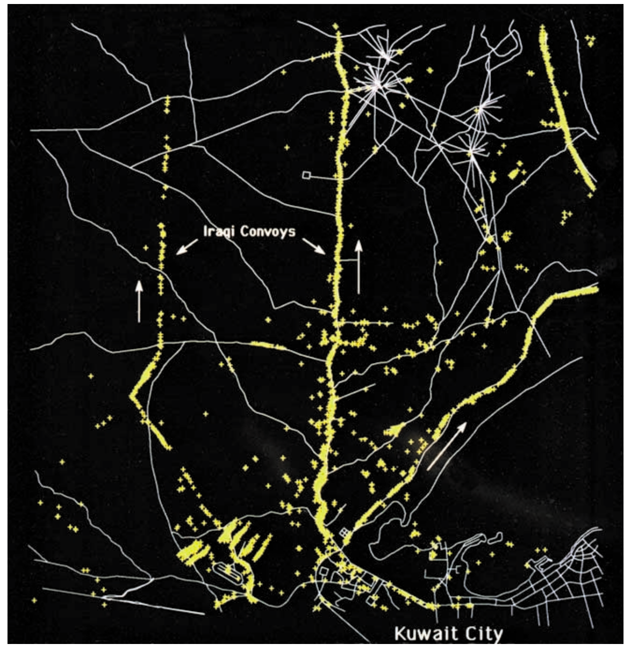

FIGURE 11. Retreat of Iraqi forces from Kuwait during the Persian Gulf War of 1991 as shown on a Joint STARS workstation. Each plus represents a vehicle or group of vehicles retreating north along several different roadways. Image courtesy of Northrop Grumman Corporation [10].

In December 1995, Joint STARS was again called into action in support of NATO peacekeeping forces in Bosnia. The Air Force accepted the first production Joint STARS (E-8C) on 22 March 1996.

The Joint STARS E-8C airborne radar was used effectively during Operation Allied Force in the deployment of aircraft and ground-based action against Yugosolavian forces operating in Kosovo. The moving and synthetic-aperture modes were used to augment the E-3 AWACS command-and-control aircraft, which had difficulty in detecting rotary-wing targets. The Joint STARS aircraft has become a standard source of information on ground-moving vehicles for all U.S. forces.

Space-Based Radar (1982–1989)

In 1982 space-based radar (SBR) was under consideration for a variety of roles, including the early detection of aircraft raids against Navy battle groups and the detection of ground moving targets such as mobile missile launchers. The originally proposed pulse-Doppler SBRs required large narrow-beam antennas to provide acceptably low Doppler spreads across the main beam. These systems needed to be in high-altitude orbits in order to maximize the coverage of individual radars so that fewer would be needed to provide the required total system coverage. As a result of the long radar ranges (e.g., 6000 nautical miles), these concepts employed powerful transmitters and very large electronically steerable antennas. Lincoln Laboratory's background in the successful demonstration of MASR led the Laboratory to consider the application of the DPCA technique to SBR.

Vincent Vitto directed a study group to research SBR. The group developed the concept of using a constellation of low-altitude satellites [12] in circular orbits at about 600 nautical miles altitude (approximately the lower limit of the Van Allen belt, in which heavy shielding is required to protect sensitive solid state electronics). These radars would have maximum radar ranges of 2000 miles to the earth's horizon. The constellation of twelve to fourteen radar satellites would be deployed to cover a large fraction of the earth at any one time and require radiation-resistant transmitters and antennas. Low-altitude satellites would be visible from a smaller area of the earth than high-altitude satellites and thus less vulnerable to ground-based jammers. In addition, ECCM techniques such as antenna nulling could be employed to suppress both interference and jamming.

The upper left corner of Figure 12 shows the configuration most often analyzed—a phased-array antenna radar with monopole radiators rigidly mounted on a back plane and oriented so that the monopoles point toward the earth's center. Each monopole would be connected to a transmit/receive (T/R) module. The modules would be fed by a transmitting distribution network and two or more receiving distribution networks. Each T/R module would contain separate digitally controlled phase shifters and attenuators for each distribution network, allowing excitation and weighting of any desired portion of the antenna. Figure 12 shows the antenna pattern of a single monopole near the center of a 121-element monopole array in which the peak gain is in the desired search region and a null exists in the direction of the earth's center, the direction of greatest ground-clutter return.

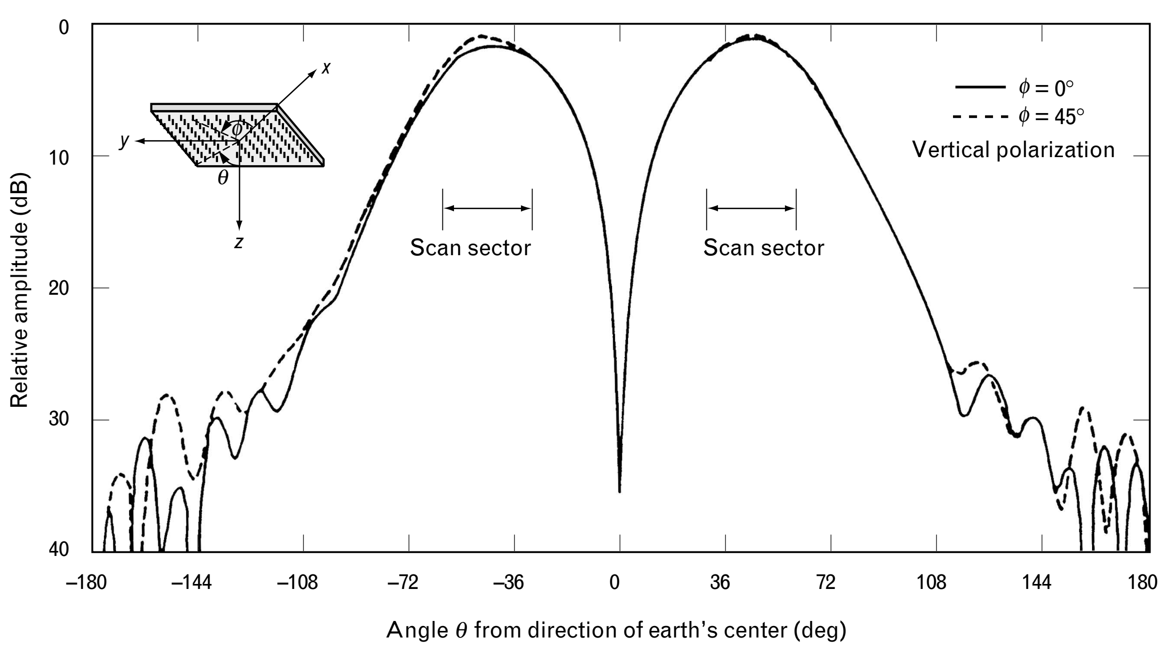

FIGURE 12. Measured radiation pattern at 1.3 GHz for two polar scanning angles ϕ of a single monopole embedded in a 121-element monopole array. The desired scan sector for the whole array (30° to 60° from the vertical) is indicated.

Theoretical Analysis

Comparing the proposed SBR to MASR reveals several important differences necessitating the use of somewhat different techniques. These techniques, as described below, have been carefully analyzed. In the MASR, the low aircraft speed permitted the utilization of a low-PRF waveform with sequential DPCA action in which a full T/R cycle was completed, then the phase center was displaced and the cycle repeated. The PRF is low enough so that second-time-around clutter from the first transmission is very low and does not interfere with the second-phase-center clutter. A SBR utilizing the DPCA technique, because of its high speed with respect to its ground track, must use a higher PRF to avoid too great a displacement of the phase center along the antenna, thus narrowing the radiating portion of the antenna and causing lower antenna gain and a broader antenna beamwidth. For reasonable-length SBR antennas, a medium or high PRF should be used. With high PRF, because of the long range of the radar, clutter returns are simultaneously received from many range-resolution cells and the total clutter load increases significantly. To overcome multiple-time-around interference, the SBR transmits all pulses from the whole antenna and simultaneously receives from two or three phase centers equally spaced around the center of the antenna. The received signals from two phase centers should be almost identical, with the first signal delayed so as to align the two effective T/R phase centers. Because of the uniform transmission pattern, the multiple-time-around clutter samples are almost identical. Further problems introduced by the higher PRF include range eclipsing and target-range ambiguities. They can be solved by using multiple PRFs.

Other differences between SBR and MASR have to do with the method of refining the azimuth accuracy of targets and the order of processing the received signals. MASR employed a sum and a difference pattern to obtain a monopulse estimate of the target's azimuth. The proposed SBR has a third receiving phase center at the middle of the antenna. Simultaneous DPCA operation between two sets of adjacent phase centers allows an accurate estimation of the target's azimuth from the resulting phase difference in a manner similar to an interferometer. Use of the ASAR technique described earlier can compensate for the increased phase and amplitude errors expected in a full phased array.

Robert W. Miller developed formulas for estimating the error mechanisms that degrade the DPCA performance of a typical SBR. These formulas include phase-center offset caused by antenna-attitude errors and timing errors, antenna deformation by bowing and twisting, frequency-response mismatch between receiver channels, T/R-module amplitude and phase errors, sidelobe clutter, analog-to-digital conversion, and internal clutter motion.

Antenna Investigations

The principal considerations in the SBR antenna design were the element radiating patterns for vertical and horizontal polarizations, the effect of mutual coupling on DPCA performance, and the method of calibration of the element-transmit/receive-distribution network combination.

Several forms of radiating elements were examined [13, 14] for their radiation patterns when embedded in a small array. Figure 12 shows that for vertical polarization, the simple vertical monopole produces a radiation pattern covering the desirable look angles with a null toward the earth's center. For horizontal polarization a loop-fed slotted cylinder produces a similar pattern. A loop-and-monopole dual-polarized element showed good horizontally polarized performance; however, vertically polarized performance was not optimized.

Most of the significant mutual-coupling effects were measured in a large array of simple monopoles. A finite-array analysis was used to compute the center-element gain pattern and input impedance as a function of the array size and element position [15]. Measurements of the element gain pattern and the mutual coupling for a 121-element passively terminated monopole square lattice array were shown to be in good agreement with theory.

Ground-based phased arrays are typically calibrated by using either a far-field or a near-field test source. However, for airborne or space-based applications, external test sources may be impractical or difficult to implement because of the great distance to

FIGURE 13. Photograph of hexagonal-spaced 96-element test array inside the radome of the far-field antenna measurement range. The array has a total of 192 elements, but the outer two rows around its circumference are terminated with matched loads to reduce boundary effects on the antenna patterns.

the far field (typically one to 10 km). A new mutual-coupling technique (MCT) for calibration, applicable to a phased array such as the DPCA SBR, having dual beam formers that can be used to select T/R element pairs, has been developed and demonstrated [16]. This calibration method enforces invariance of the mutual coupling through all adjacent-element channels to provide uniform illumination. For a desired array illumination, errors due to array-weight quantization are then measured by a second application of MCT. Array radiation patterns can be calculated from the measured array, the known array-element positions, and a known embedded element pattern.

An experimental investigation of array mutual coupling produced good agreement with conventional far-field calibration and pattern measurements of a 96-element corporate-fed phased-array antenna, shown in Figure 13. Two-dimensional radiation patterns using MCT were achieved and demonstrated.

In another interesting investigation the effect of mutual coupling between array radiating elements on DPCA performance was theoretically determined [17]. The method of moments was used in a numerical simulation to model SBR arrays. Upper-bound DPCA clutter-cancellation capability, in terms of pattern match, was presented. Other issues that were investigated include the influence of main-beam scan angle, array illumination, phase-center displacement, array size, array lattice, number of passively terminated element guard bands, and radiating-element type on two-phase-center DPCA clutter cancellation. Dipole and monopole arrays having square and hexagonal lattices were analyzed. It was shown quantitatively that variation in the above parameters substantially influences the DPCA clutter cancellation. As an example of the results, Figure 14 shows the theoretical and measured cancellation performance of the 96-element monopole test array, which has two guard bands surrounding the 96 active elements. Cancellation is shown as a function of phase-center displacement with scanning angle off the direction toward the earth's center as a parameter. The measured cancellation is about 10 dB less than the theoretical. In this case, the measured cancellation performance is largely determined by other effects (e.g., phase and amplitude errors) rather than mutual-coupling effects. Many of these potential error sources can be reduced by using clutter-adaptive cancelers, especially in a post-Doppler adaptive-DPCA mechanization.

The Space Radar Technology program at Lincoln Laboratory was conducted for about ten years. In addition to the investigations described above, other analyses and experiments were conducted in order to reduce the technical risk associated with such an ambitious radar system [18]. A major difficulty anticipated for such a system would be to suppress multiple high-power ground-based sidelobe jammers while also maintaining the high level of clutter suppression required. This suppression requires that the two- or three-phase-center DPCA processing be augmented to include the simultaneous suppression of jamming, using four to ten sidelobe cancellation channels for each phase center. This was to be accomplished by using a special form of space-time adaptive processing. The resulting requirements on signal processing and channel accuracy were particularly challenging [19, 20]. Through a sequence of experiments and analyses, the technology necessary for simultaneous suppression of better than 40 dB for clutter and 50 dB for jamming was established.

At the end of the 1980s, with the cessation of the

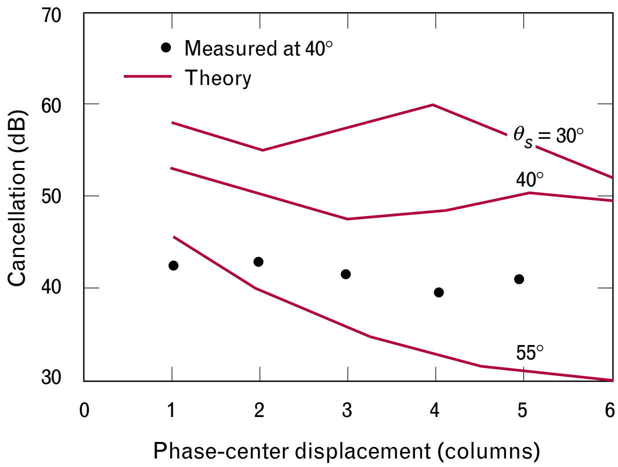

FIGURE 14. Theoretical and measured cancellation of a dual-phase-center 96-element array as a function of the phase-center displacement, with the polar scanning angle θ_s as a parameter. The curves are derived from theory and the dots from measurements for a 40° scanning angle.

Cold War, the perceived need for an SBR system for air defense or ground surveillance declined and the Space Radar Program at Lincoln Laboratory was concluded. Many of the technical advances have been carried over into other radar programs. Lincoln Laboratory continues to participate in SBR studies that are undertaken from time to time, and as of this writing the Defense Advanced Research Projects Agency (DARPA), the Air Force, and the National Reconnaissance Office (NRO) have initiated a major national development program in ground surveillance with space-based radar. Lincoln Laboratory is participating in this initiative under the sponsorship of DARPA. The program, called Discoverer II, will feature MTI radar including variations on the DPCA techniques.

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received a B.S. degree in electrical engineering from Seattle University in 1950 and an S.M. degree from MIT in 1952. After teaching at Seattle University for four years he joined the Microwave Components group at Lincoln Laboratory. Of the microwave systems he helped develop the most notable were used on the Laboratory's Haystack planetary radar in the fourth test of Einstein's general theory of relativity and on ALCOR at the Kwajalein missile test range, which is capable of imaging reentry vehicles and satellites. In 1967 he became associate leader, and in 1968 leader, of a group that designed, built, and tested complete prototype radar systems. The first was a radar used in Vietnam to detect people walking under dense foliage. Starting in 1972 Ed's group developed digital signal and data processors capable of completely automatic detection, tracking, and displaying of moving targets in heavy clutter. This accomplishment led to a netted radar system demonstrated by the Army Artillery at Fort Sill, Oklahoma, an airborne radar to detect slowly moving ground vehicles (the progenitor of the Joint STARS radar), and the prototype of a widely employed FAA Airport Surveillance Radar (ASR-9). For seven years Ed served as radar editor of the *IEEE Aerospace and Electronic Systems Transactions*.

MELVIN LABITT
is a staff member in the Air Traffic Systems group, where he is now involved with the design, specifications, and follow-up of fielded radar systems such as the ASR-9 and ASDE-3. Before that he was involved in the design and analysis of foliage-penetration radar to detect personnel in heavily wooded areas. In 1964 he worked on the on-site data analysis of reentering missiles at Kwajalein as well as diagnosing and repairing the 24-in telescope servo-system used to track missiles. In 1952 he joined Lincoln Laboratory, where he first worked on airborne early warning (AEW) systems and invented the Time-Average Clutter Coherent Airborne Radar (TACCAR) system that allowed the cancellation of clutter in airborne radars. For this work he received the Pioneer Award from the IEEE in 1991. He graduated from MIT in 1951 with an S.B. degree in physics.